Sea Level Rise in the Coastal Waters of Washington State

A report by
the University of Washington Climate Impacts Group
and the Washington Department of Ecology

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January 2008

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The authors would like to thank the following persons who reviewed this report: Jim Simmonds, Supervisor for Water Quality and Quantity, and Angela Grout, Oceanographer, for King County, Washington; Dr. Ian Joughin, University of Washington Polar Science Center; Ray Weldon, Professor, University of Oregon; and Susan Tonkin, Coastal Engineer, Moffatt & Nichol. In addition, we wish to thank Dr. Tim Melbourne, Associate Professor, Andrew Miner, Researcher, and Marcelo Santillan, Scientific Programmer and GPS Data Analyst, Central Washington University, for providing Figure 8.

Note: Units less than centimeters (cm) are not converted into English units. Centimeter conversions to inches are rounded to the nearest whole unit for ease of reading.

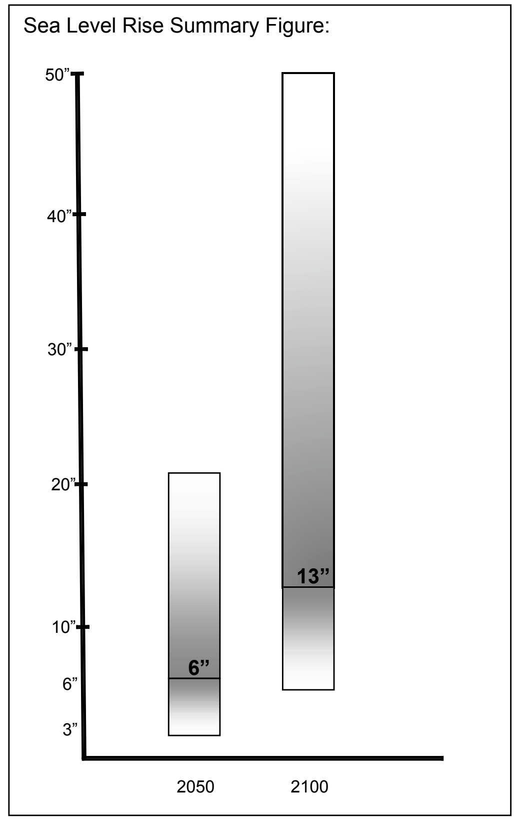
This publication is partially funded by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) under NOAA Cooperative Agreement No. NA17RJ1232, Contribution # 1474.

Photo: *Whidbey Island near Fort Casey. Photo by Philip Mote.*

Summary. Local sea level rise (SLR) is produced by the combined effects of global sea level rise and local factors such as vertical land deformation (e.g., tectonic movement, isostatic rebound) and seasonal ocean elevation changes due to atmospheric circulation effects. In this document we review available projections of these factors for the coastal waters of Washington and provide low, medium, and high estimates of local SLR for 2050 and 2100.

The fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) projects global SLR over the course of this century to be between 18 and 38 cm (7-15") for their lowest emissions scenario, and between 26 and 59 cm (10-23") for their highest emissions scenario. **Based on the current science, our "medium" estimate of 21st century SLR in Washington is that in Puget Sound, local SLR will closely match global SLR. On the northwest Olympic Peninsula, very little relative SLR will be apparent due to rates of local tectonic uplift that currently exceed projected rates of global SLR.** On the central and southern Washington coast, the number of continuous monitoring sites with sufficiently long data records is small, adding to the uncertainty of SLR estimates for this region. Available data points suggest, however, that uplift is occurring in this region, but at rates lower than that observed on the NW Olympic Peninsula.

The application of SLR estimates in decision making will depend on location, time frame, and risk tolerance. For decisions with long timelines and low risk tolerance, such as coastal development and public infrastructure, users should consider low-probability high-impact estimates that take into account, among other things, the potential for higher rates of SLR driven by recent observations of rapid ice loss in Greenland and Antarctica, which though observed were not factored into the IPCC's latest global SLR estimates. **Combining the IPCC high emissions scenario with 1) higher estimates of ice loss from Greenland and Antarctica, 2) seasonal changes in atmospheric circulation in the Pacific, and 3) vertical land deformation, a low-probability high-impact estimate of local SLR for the Puget Sound Basin is 55 cm (22") by 2050 and 128 cm (50") by 2100.** Low-probability, high impact estimates are smaller for the central and southern Washington coast (45 cm [18"] by 2050 and 108 cm [43"] by 2100), and even lower for the NW Olympic Peninsula (35 cm [14"] by 2050 and 88 cm [35"] by 2100) due to tectonic uplift (see Table III). The authors intend to continue investigating the factors contributing to local SLR and will provide updates to this report.



Projected sea level rise in Washington's waters relative to 1980-99, in inches. Shading roughly indicates likelihood.

1. Background

Sea level rise (SLR) is increasingly being considered by private and public entities when making decisions about the placement and protection of structures near shorelines. The Climate Impacts Group (CIG) at University of Washington has recently received inquiries from several municipalities, consultants, and private citizens concerning the likely rates of SLR at specific locations in the waters of Washington State during the 21st century. This document is intended to address those questions and to provide guidance on the use of SLR projections.

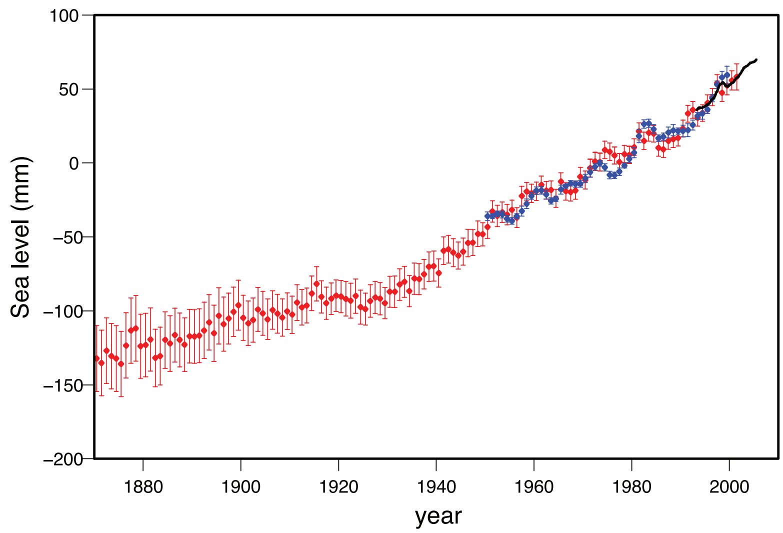


Figure 1. Annual averages of the global mean sea level (mm). The red curve shows reconstructed sea level fields since 1870, the blue curve shows coastal tide gauge measurements since 1950, and the black curve is based on satellite altimetry. Error bars show 90% confidence intervals. Figure 5.13 from IPCC (2007).

2. Observed rates of global sea level rise

Global estimates of SLR (Figure 1) can be derived by considering tide gauge records in combination with models or actual measurements of Earth's local tectonic movement. The average rate of global SLR for 1961-2003 is 1.8 ± 0.5 mm/yr (IPCC SPM, 2007). Satellite altimetry measurements by the TOPEX/ Poseidon and Jason 1 satellites covering the years 1993-2003 provide a value of 3.1 ± 0.7 mm/yr (IPCC 2007, Nerem et al. 2006).

Table I shows the estimated contribution of various processes to observed SLR during those two time periods. The agreement between the sum of contributions and the observed change in SLR is substantially better for the 1993-2003 period than for the 1961-2003 period, and the difference between the sum and the observed change is no longer statistically significant. This convergence is due mainly to improvements in data collection techniques. For the 1993-2003 period, the largest term (and the largest increase from the previous era) is the thermal expansion term.

Table I. SLR contributions in mm/yr, from IPCC 2007 (Table 5.3). See also Figure 2.

Source	**1961-2003**	**1993-2003**
Thermal expansion	0.42 ± 0.12	1.6 ± 0.5
Glaciers and ice caps	0.5 ± 0.18	0.77 ± 0.22
Greenland ice sheet	0.05 ± 0.12	0.21 ± 0.07
Antarctic ice sheet	0.14 ± 0.41	0.21 ± 0.35
Sum	1.1 ± 0.5	2.8 ± 0.7
Observed	1.8 ± 0.5	3.1 ± 0.7
Difference	0.7 ± 0.7	0.3 ± 1.0

3. Sea level rise projections

Four main drivers of local SLR are (1) global SLR (Table II and Figure 3) driven by the thermal expansion of the ocean; (2) global SLR driven by the melting of land-based ice; (3) local dynamical SLR driven by changes in wind, which push coastal waters toward or away from shore; and (4) local dynamical SLR driven by local movement of the land itself, due primarily to tectonic forces. We now discuss each of these factors. Changes related to the storage of surface water in reservoirs and aquifers are estimated to be substantially smaller than the other terms and thus are not discussed.

3.1 Thermal expansion

The ocean has absorbed roughly 80% of the heating of the climate system associated with rising greenhouse gases during the past ~50 years (IPCC SPM 2007), leading to substantial ocean warming. Because seawater expands slightly when warmed, the volume of the ocean has increased and the ocean is expected to continue expanding as a result of projected increases in 21st century global temperature.

feet), substantially higher than the IPCC projections. While caution must be used in extrapolating a linear relationship so far beyond the 20th century variability used to derive it, Rahmstorf's findings provide a scientific basis for considering much higher rates of sea level rise than the current IPCC projections.

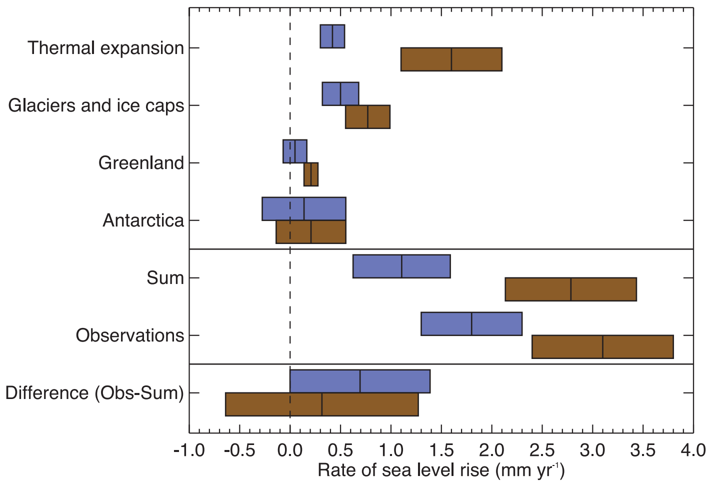


Figure 2. Estimates of the various contributions to the budget of the global mean sea level change (upper four entries), the sum of these contributions and the observed rate of rise (middle two), and the observed rate minus the sum of contributions (lower), all for 1961 to 2003 (blue, top bar in each pair) and 1993 to 2003 (brown, bottom bar). The bars represent the 5-95% error range. Fig 5.21 from IPCC (2007).

Table II. Sea level rise contributions 2090-99 minus 1980-99, expressed in mm/yr for comparison with Table I. Reformatted from IPCC (2007) Table 10.7.

Source	**B1**	**A1FI**
Thermal expansion	1.7± 0.7	2.9±1.2
Glaciers and ice caps	1.05±0.35	1.25±0.45
Greenland ice sheet	0.3±0.2	0.7±0.5
Antarctic ice sheet	-0.6±0.4	-0.85±0.55
Sum	2.8±1.0	4.25±1.65
Sum *(meters per century)*	0.28±0.10	0.425±0.165

This fact, when combined with the long timescale of ocean thermal expansion, has significant long-term implications for SLR. Ocean thermal expansion will continue for ~1000 yr after atmospheric temperature stabilizes as the slow circulation of the deep ocean gradually brings older cold water into contact with the new conditions.

The IPCC generated a range of scenarios of socioeconomic change during the 21st century, which in turn lead to a range of projected temperature and SLR changes. These scenarios range from the low B1 scenario, in which carbon dioxide rises to roughly double its pre-industrial concentration by 2100, to the high A1FI scenario, in which carbon dioxide reaches 3.5 times its preindustrial concentration.

Projected thermal expansion for the 21st century ranges from 17±7 cm (7”±3”) for IPCC’s low emissions B1 scenario to 29±12 cm (11”±5”) for the IPCC’s high emissions A1FI scenario (see Table II and Figures 3 and 4). Overall, thermal expansion accounts for about one-half of projected 21st century SLR.

A recent paper (Rahmstorf 2007) noted a strong relationship between observed global temperature and rate of SLR per unit of time. Using a linear relaxation model (i.e., SLR equilibrates to a change in temperature over a long period), Rahmstorf used the 20th century relationship together with future scenarios of temperature change from IPCC to infer that 21st century SLR from thermal expansion alone could be in the range 0.5-1.4 m (1.6-4.6

3.2 Cryospheric contribution

Melting of global ice (the cryosphere) provides another substantial contribution to global SLR. Melting of glaciers and ice caps is presently, and is projected to remain, the largest cryospheric contribution to SLR. However, several independent measurements of Greenland and Antarctic mass balance using lasers and gravity measurements indicate that both Greenland and Antarctica have recently (2002-2006) been substantial contributors to global SLR (IPCC 2007, pp. 363-366; Zwally et al. 2006, radar altimetry; Thomas et al. 2006, laser altimetry; Velicogna and Wahr 2005, 2006, satellite gravity measurements). In stark contrast to these observations, the IPCC projections (Figure 3 and Table II) assume that Antarctica alone and the sum of contributions by Greenland and Antarctica will (with 95% confidence) tend to offset, not add to, sea level throughout the 21st century as increased precipitation in Antarctica increases the mass balance of the continent. In effect, the IPCC has dismissed recent observations of substantial SLR contribution from Greenland and Antarctica as nothing more than a brief excursion away from the true long-term mass balance.

Several physical processes appear to be contributing to the recent large contributions from Greenland. These include basal melting, ice flow accelera-

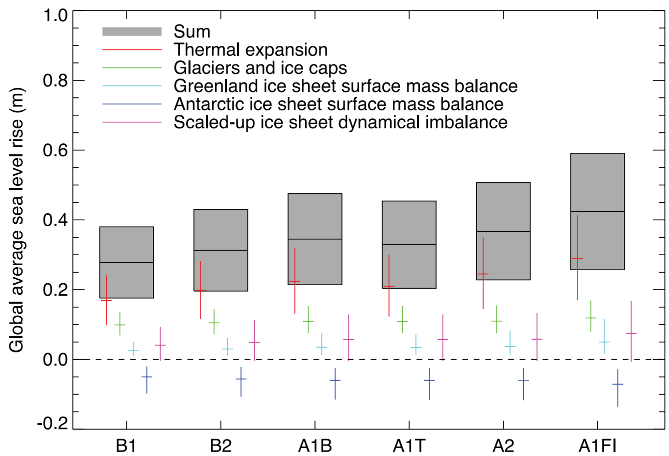


Figure 3. Projections and uncertainties (5 to 95% ranges) of global average sea level rise and its components in 2090 to 2099 (relative to 1980 to 1999) for the six SRES marker scenarios. The projected sea level rise assumes that the part of the present-day ice sheet mass imbalance that is due to recent ice flow acceleration will persist unchanged. It does not include the contribution shown from scaled-up ice sheet discharge, which is an alternative possibility. It is also possible that the present imbalance might be transient, in which case the projected sea level rise is reduced by 0.02 m. It must be emphasized that we cannot assess the likelihood of any of these three alternatives, which are presented as illustrative. The state of understanding prevents a best estimate from being made. From IPCC (2007).

tion, and other nonlinear ice dynamics. For example, after the Larsen-B ice shelf (east of the Antarctic peninsula) disintegrated in 2002, numerous glaciers feeding the ice shelf accelerated with the removal of the back-pressure of the ice shelf. IPCC projections of future SLR included the possibility of continued rapid ice loss through these processes, but they were not discussed in the widely read summary for policymakers, only deep within the IPCC report. This factor is illustrated in Figure 3 as "scaled-up ice sheet discharge" or "dynamical imbalance", and it was estimated at levels substantially smaller than recent observations would suggest. Furthermore, it was based on a poorly understood relationship in the 1993-2003 period between a global temperature anomaly 0.63°C (1.1°F) and possible ice-sheet dynamical contribution to sea level rise of 0.32mm/yr (IPCC 2007, Appendix 10.A.5). We will argue below that for the very high estimate of SLR, these factors warrant more careful attention.

3.3 *Local atmospheric circulation*

The presence of a northward wind along the outer coast plays a significant role in local sea level on seasonal and interannual timescales. The wind-driven enhancement of sea level occurs because the northward wind, common during winter months (and even more prevalent during El Niño events) combines with the effects of Earth's rotation to push ocean water toward shore, elevating sea level. The result is that mean wintertime sea level is roughly 50 cm (20") higher than summer sea level on Washington's coasts and estuaries (Figure 5), and during El Niño events, sea level can be elevated by as much as an additional 30 cm (12") for several months at a time (Ruggiero et al. 2005).

Given the strength of this effect locally, it is important to consider the possible future changes in atmospheric circulation over the North Pacific. Figure 6 shows the estimates of sea level change as a result of changes in atmospheric circulation and in ocean density, averaged over 18 models for the moderate IPCC A1B emissions scenario. For the coast of

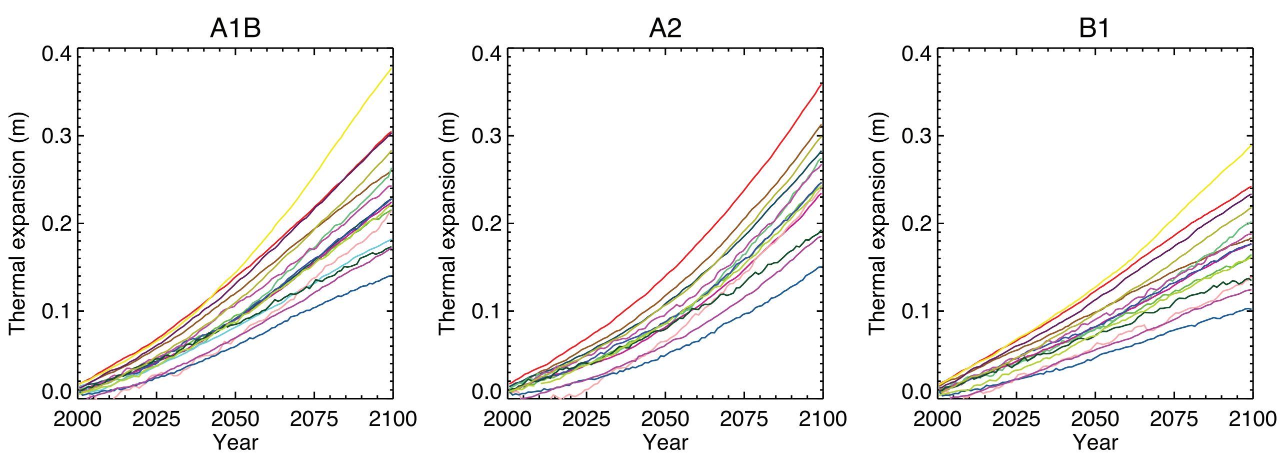


Figure 4. Projected global average sea level rise (m) due to thermal expansion during the 21st century relative to 1980 to 1999 under emissions scenarios A1B, A2, and B1. Colored curves refer to different global climate models. From IPCC (2007).

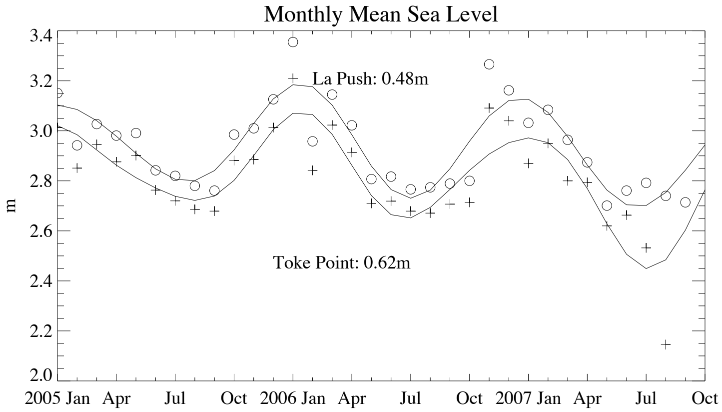


Figure 5. Monthly mean sea level in meters for January 2005 through September 2007 at La Push and Toke Point (Willapa Bay), Washington. Monthly average values for La Push and Toke Point are shown as circles and crosses, respectively. Figure source: Climate Impacts Group, University of Washington.

western North America, the sum of these contributions in the annual mean is about 2-3 cm (about 1") *below* the global average.

CIG has analyzed over 30 scenarios from global climate models (Mote et al. 2007) and the mean changes in wintertime northward wind are indeed minimal. Consequently, we subtract 1 and 2 cm (less than 1") from the "very low" SLR estimates for 2050 and 2100, respectively, and consider this component to be negligible for the "medium" SLR estimate. However, several models produce increases in northward wind in wintertime of sufficient strength to add as much as 15 cm (6") to mean sea level for 2050-2099 compared with 1950-1999, so for the "very high" SLR estimate we add 15 cm (6").

3.4 Local tectonic movement

Direct measurements of sea level at tide gauges are difficult to interpret because tide gauges record the difference between local sea level and local land level, with interannual variability and measurement uncertainty clouding the picture. Differences in rates of sea level rise can be substantial. For example, the linear trend in sea level for 1973-2000 was 2.82±1.05 mm/yr at Toke Point (Willapa Bay, southern coast) and 1.39±0.94 mm/yr at Cherry Point (near Bellingham; Zervas 2001). Without additional evidence it is difficult to separate sea level rise from local land level change, which itself could be caused by a variety of factors including tectonic movement or soil compaction. Trends also change over time: 50-year trends at Seattle (1898-2000) range from 1.04 mm/yr to 2.80 mm/yr (*ibid*). Linear trends are influenced by fluctuation in annual and decadal rates of global sea level rise as well as variations in the rate of local vertical land movement (VLM).

Deducing the contribution of local VLM formerly required a model of Earth's crustal movement. Recently, direct measurements of sea level from satellites, and of land movement from global positioning system (GPS) sensors, have improved our understanding of these two contributions to tide gage measurements of sea level.

Crustal deformation associated with plate tectonics and isostatic rebound (adjustments to the disappearance of the great ice sheets) produces local vertical land movement. Western Washington sits on the edge of the North American continental plate, under which the Juan de Fuca oceanic plate is subducting. This subduction tends to produce uplift in the western extent of the region over time (although historically, large subduction zone earthquakes of magnitude > 8.0 in the region have resulted in sudden land subsidence of 1 meter (3.3 ft) or more [Leonard et al. 2004, Jacoby et al. 1997]).

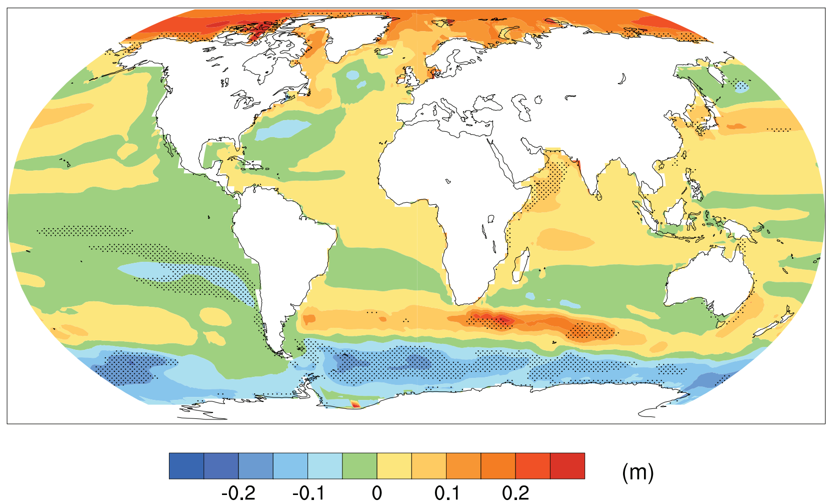


Figure 6. Local sea level change (m) due to ocean density and circulation change relative to the global average (i.e., positive values indicate greater local sea level change than global) during the 21st century, calculated as the difference between averages for 2080 to 2099 and 1980 to 1999, as an ensemble mean over 16 AOGCMs forced with the SRES A1B scenario. Stippling denotes regions where the magnitude of the multi-model ensemble mean divided by the multi-model standard deviation exceeds 1.0. From IPCC (2007).

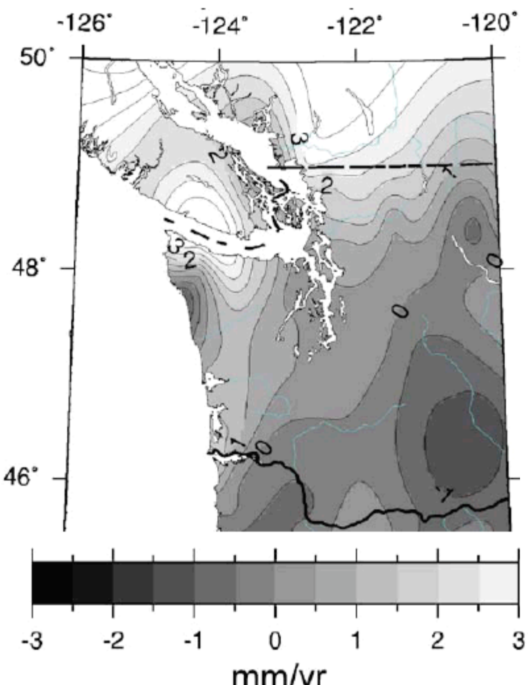


Figure 7. Vertical land movements, from Verdonck (2006).

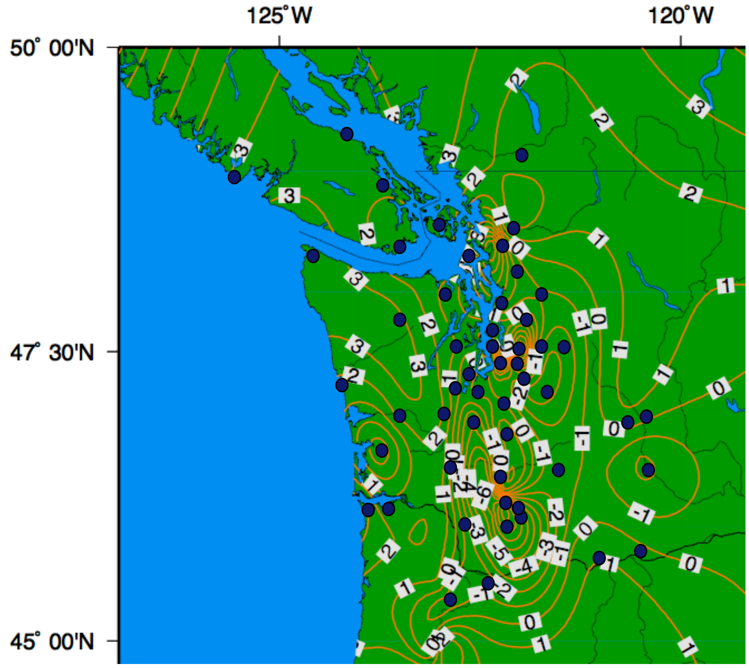


Figure 8. GPS derived current annual vertical deformation rates (mm/year), from Pacific Northwest Geodetic Array (stations indicated by symbols), Central Washington University, November 2007, www.geodesy.org

An earlier analysis of records in the Pacific Northwest (Holdahl et al. 1989) suggested that south Puget Sound was subsiding at a rate of approximately 2 mm/yr and the northwest Olympic Peninsula was rising at a comparable rate, while VLM on most of the Washington coast and the rest of Puget Sound was mostly less than 1 mm/yr. Another study by Mitchell et al. (1994) found little VLM in Puget Sound, but similar VLM for the coast as those of Holdahl et al. (1989).

More recently, Verdonck (2006) recalculated VLM and again found uplift, but at a rate as high as 3.5 mm/yr on the north and northwest part of Olympic Peninsula, only small movement in central and southern Puget Sound, and some strong local subsidence on the central Washington coast (Figure 7). However, ongoing GPS measurements at Pacific Beach, WA suggest uplift in this region of the outer coast of 1.8 mm/yr. Recent analysis of continuous GPS monitoring sites comprising the Pacific Northwest Geodetic Array (PANGA) by staff at Central Washington University support the conclusion of general uplift occurring along most of the outer coast with the greatest uplift (>3mm/yr) located in the northwest corner of the Olympic Peninsula and with uplift dropping off to near zero in the central Puget Sound (Figure 8).

Thus, it appears that the method of analysis and the time period studied lead to different estimates of VLM, except in the northwest corner of the Olympic Peninsula where all three studies, and current observations, agree on uplift at >2 mm/yr. Reliable estimates of VLM for the central and southern Washington coast are not available due to sparse data, but are estimated to be on the order of 0-2 mm of uplift per year.

The Puget Sound basin seems to be the least consistent. Based on current analysis we do not believe we can justify factoring VLM into the "very low" and "medium" SLR estimates for Puget Sound. However, for the upper or "very high" SLR estimate (high impact, low-probability) for the Puget Sound basin, we assume subsidence of 10 cm (4") by 2050 and 20 cm (8") by 2100 on the basis of the Verdonck (2006) data set. Rates of tectonic uplift were incorporated into the SLR estimates for the northwest corner of the Olympic Peninsula and the "very low" and "medium" estimates for central and southern Washington coast. Again, because of the characteristics of the "very high" SLR estimate, VLM along the central and southern coast is removed to reflect a scenario of zero or negligible uplift in this region.

Local areas of subsidence due to sediment compaction in estuaries and coastal basins as well as subsidence in terrain overlying areas that have experienced significant groundwater extraction are not considered in this report, but could very well dominate smaller scale relative SLR and its variability throughout the region.

4. Synthesis: Summary and calculation of SLR projections

Three important questions need to be considered in the use of SLR estimates in decision making:

1) what is the location of interest?
2) what time horizon should be considered?, and
3) what risk level is acceptable?

As indicated by Sections 3.3 and 3.4, location is important as rates of SLR vary depending on oceanographic conditions and on local VLM.

Time horizon is very important and will be defined by the nature of the decision being made; decisions with long life spans or long-term implications should be based on longer-term estimates of sea level rise. Note that time horizon is not just a function of the lifespan of a specific structure. The choice of time horizon should take into account the overall "footprint" of the decision, i.e., the committed long-term use of the site once it is developed.

For some factors that contribute to local SLR, changes will probably be linear with time so the 2050 value will be half the 2100 value. However, this is not the case for the most important term, global SLR: in most scenarios the *rate* of global SLR increases over time (the curve is concave upward or accelerating). Hence, it is inappropriate to estimate SLR in 2050 simply by halving an estimate of change that applies to the year 2100.

Finally, risk tolerance determines whether the medium or a less likely but higher (or lower) impact estimate is used. Risk tolerance will vary from community to community, person to person, and project to project.

We now attempt to combine the factors in the above discussion to construct estimates of SLR for the NW Olympic Peninsula, the central and southern Washington coast, and Puget Sound for 2050 and 2100 (Table III). **We stress that (1) these calculations have not formally quantified the probabilities, (2) SLR cannot be estimated accurately at specific locations, and (3) these numbers are for advisory purposes and are not actual predictions**.

For the end-of-century "very low" SLR estimate, we use the 5% value of the B1 SLR scenario, namely 18 cm (7") by 2100. The atmospheric component is assumed to be the same for all three areas and contributes –2 cm (less than –1"). For local contributions from VLM we take the low end of the various estimates discussed above: uplift in the NW Olympic Peninsula of 4 mm/yr (translates to a local SLR of –16" per century) and no uplift for Puget Sound. Uplift for the central and southern Washington coast is estimated at 1 mm/year (translates to a SLR of about –4" per century). Furthermore, global temperatures in the B1 scenario level off by 2100. Consequently, the SLR profile is approximately linear (Figure 4), so the values in 2050 are half those in 2100.

For the end-of-century "medium" SLR estimate, we use the average of the six central values from the six IPCC scenarios (34 cm or 13"). The value for 2050 is somewhat below half of this value owing to the acceleration of SLR in all scenarios except B1 (Figure 4), with a low of 39% for A2 and a high of 50% for B1 and a mean of 45%. The atmospheric contribution is approximately zero. For the VLM term, we take the uplift value of 3mm/yr (translates to a SLR of –12" per century) for the NW Olympic Peninsula and 0.5 mm/yr (translates to a SLR of –2" per century) for the central and southern coast. For the Puget Sound basin, we again assume no change.

For the end-of-century "very high" SLR estimate, we start with the A1FI 95% value of 59 cm (23") by 2100 but allow the possibility that the recent cryospheric contributions could continue and even increase in the 21st century. Although it is difficult to quantify the importance of such processes over the span of the 21st century, we take as a starting point the calculation in IPCC 2007 (Appendix 10.A.5). They presumed a linear relationship between global temperature anomalies (0.63°C) and enhanced ice sheet loss from these dynamical processes (0.32 mm/yr), and arrived at an estimate of 0-17 cm (0-7") for the 21st century SLR. However, observations cannot constrain their estimate of 0.32 mm/yr within a factor of two. For example, one could posit a situation in which the difference between observed SLR and the sum of known terms during 1993-2003 (Table I) is entirely due to these processes; this gives an upper estimate of 1.3mm/yr, roughly a factor of 4 larger than their estimate. Likewise, there are small uncertainties in the estimated global temperature anomaly used in this ratio. Since an error of a factor of two in this ratio is plausible, we take that as a rough estimate of the upper limit of ice sheet contributions, adding 34 cm (13") for 2100.

The atmospheric contribution in all areas is 15 cm (6") by 2100 and 7 cm (3") for 2050.

For the VLM term in our "very high" SLR estimate, we use an uplift value of 2 mm/yr (SLR about –8" per century) at the NW Olympic Peninsula. For the central and southern Washington coast, we assume zero VLM. For the Puget Sound region, subsidence of 2 mm/year (SLR about 8" per century) is used.

5. Unknowns and additional considerations

We reiterate that the four factors discussed here are not well quantified. Future contributions to SLR from Greenland and Antarctica are very uncertain. The rates of VLM at specific locations are generally poorly understood and it is impossible to estimate the uncertainty associated with using measurements of VLM in the recent past to predict changes over the next century. Additionally, we have not developed a formal framework to quantify the probabilities of our "very high" or "very low" SLR estimates.

As additional studies of these subjects are published, a thorough assessment of the state of science would be warranted, along with a more careful quantification of probabilities and uncertainties. We have assumed independent probabilities in combining estimates of global SLR (which the IPCC made using a combination of global climate models and simpler models) and local atmospheric dynamical factors, whereas a more rigorous analysis would use the SLR output of the global models directly.

Finally, our analysis has focused on the slow change in mean sea level. Societal and ecological impacts will be driven at least as much by the sequence of extreme events as by the slow change in the mean. That is, a coastal inundation event could be produced either by our "very high" sea level plus a moderate high tide and storm surge, or by our "very low" sea level plus an exceptionally high tide and storm surge. Whether such an event occurs in 2009 or 2099 depends as much on the random confluence of events as on the background change in sea level driven by anthropogenic global climate change.

Table III. Calculation of very low, medium, and very high estimates of Washington sea level change for 2050 and 2100, in cm (and, for totals, inches). VLM and and Total (the sum of factors used to calculate the total relative SLR value) are reported for NW Olympic Peninsula, the central and southern Washington coast, and Puget Sound. Negative VLM values represent vertical uplift of the land and a negative Total represents an apparent or relative sea level drop. Both the very low and very high SLR estimates are considered low probability scenarios.

SLR Estimate	Components	2050			2100		
		NW Olympic Peninsula	Central & Southern Coast	Puget Sound	NW Olympic Peninsula	Central & Southern Coast	Puget Sound
Very Low	Global SLR	9 cm			18 cm		
	Atm. Dynamics	-1 cm			- 2 cm		
	VLM	-20 cm	- 5cm	0 cm	- 40 cm	-10 cm	0 cm
	Total	**-12 cm (-5")**	**3 cm (1")**	**8 cm (3")**	**-24 cm (-9")**	**6 cm (2")**	**16 cm (6")**
Medium	Global SLR	15 cm			34 cm		
	Atm. Dynamics	0 cm			0 cm		
	VLM	- 15 cm	- 2.5 cm	0 cm	-30 cm	- 5 cm	0 cm
	Total	**0 cm (0")**	**12.5 cm (5")**	**15 cm (6")**	**4 cm (2")**	**29 cm (11")**	**34 cm (13")**
Very High	Global SLR	38 cm			93 cm		
	Atm. Dynamics	7 cm			15 cm		
	VLM	-10 cm	0 cm	10 cm	- 20 cm	0 cm	20 cm
	Total	**35 cm (14")**	**45 cm (18")**	**55 cm (22")**	**88 cm (35")**	**108 cm (43")**	**128 cm (50")**

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